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DAMAGE ASSESSMENT OF STRUCTURES AN AIR FORCE OFFICE OF SCIENTIFIC RESEARCH STRUCTURAL MECHANICS PERSPECTIVE

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Abstract: *This paper presents the perspective of the Structural Mechanics program of the Air Force Office of Scientific Research on the damage assessment of structures. It is found that damage assessment of structures plays a very important role in assuring the safety and operational readiness of Air Force fleet. The current fleet has many aging aircraft, which poses a considerable challenge for the operators and maintainers. The nondestructive evaluation technology is rather mature and able to detect damage with considerable reliability during the periodic maintenance inspections. The emerging structural health monitoring methodology has great potential, because it will use on-board damage detection sensors and systems, will be able to offer on-demand structural health bulletins. Considerable fundamental and applied research is still needed to enable the development, implementation, and dissemination of structural health monitoring technology.*

1 INTRODUCTION

The Air Force Office of Scientific Research (AFOSR) is the fundamental basic research component of the Air Force Research Laboratory. AFOSR is organized in three major research areas [1]:

- Aerospace, Chemical, and Material Sciences

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Inside each of the major research areas there are several research programs. For example, the Aerospace, Chemical, and Material Sciences Directorate research area encompasses thirteen research programs; details of these research programs can be found on the public website given in ref. 1.

One of the thirteen research programs of the Aerospace, Chemical, and Material Sciences Directorate is the research program in Structural Mechanics. The objective of the Structural Mechanics research program is [1] "to support fundamental studies in enabling structural technologies for future Air Force systems. Fundamental studies that will enable the Air Force to maintain the integrity and functionality of existing aerospace structures, as well as enhance their performance are also of great interest. White papers are sought for studies into the synergetic exploitation of large nonlinear structural deformations under coupled fluid, thermal, and mechanical loads in quasi-static and dynamic regimes. Examples include, but are not limited to, novel actuation devices, the exploitation of aeroelastic phenomena for flapping-wing micro air vehicles, the prevention and control of nonlinear and aeroelastic phenomena, energy harvesting from environmental air turbulence and structural vibration, etc. Flexible load-bearing skins and reconfigurable support structures for smart and adaptive morphing aerospace vehicles are of interest.

Novel structural concepts that support air- and space-based applications are of interest at any scale (nano, MEMS, large deployable structures) and for any purpose (sensing, control, stiffening, actuation, etc.)

Structural health monitoring, nondestructive evaluation, diagnostics and prognosis, and other concepts that contribute to the sustainment of structural reliability, survivability and mission readiness, especially under extreme environments, are of continuous interest. White papers for other structural innovations in USAF-relevant areas not specifically mentioned above are also welcomed. [1].

It is apparent from the above short overview that damage assessment of structures, nondestructive evaluation, and structural health monitoring play an important role in the AFOSR structural mechanics research program.

2 AGING AIRCRAFT FLEET

The United States Air Force (USAF) uses a varied complement of aircraft with a diverse age span, from the 1950's B-52 bombers, to the state-of-the-art multi-role F-22 and F-35 aircraft (Figure 1 through Figure 10). In the USAF fleet, an important proportion of the aircraft qualify for the "aging aircraft" description.

Figure 1: [2]

Figure 2: KC-135 Stratotanker, KC-10 Extender, F-15 Eagle, F-22 Spirit [2]

Figure 3: A-10 Thunderbolt II [2]

Figure 4: F-15 Eagle [2]

Figure 5: F-16 Fighting Falcon [2]

Figure 6: F-117 Nighthawk [2]

Figure 7: F-22 Spirit [2]

Figure 8: F-35 Lightning II JSF [2]

The decision on whether to maintain or replace an aging system is a common one. Anyone who owns an automobile, for instance, eventually grapples with this issue. At some point, it seems wrong to "throw good money after bad" and continue to repair an aging system. But replacement systems typically entail considerable up-front investment. The Air Force is facing a similar decision question in relation to several systems that have been in operation for several decades. Recent studies [3],[4] have studied the relative cost-benefit of retaining or replacing large aircraft inventories. For example, ref. [3] considered a certain aircraft type (e.g., a tanker) that the Air Force envisions having in its inventory, in some form, into the foreseeable future. Then they examined the option of operating an existing aircraft for one more year versus the option of replacing it right now.

Figure 9: C-130 Hercules [2]

Operating an existing aircraft for one more year yields some aircraft availability level at the cost of the requisite maintenance, fuel, and labor. In contrast, purchasing a new aircraft results in a stream of both costs and aircraft availability. The study [3] found that the Air Force should repair, rather than replace, an existing system if and only if the availability-adjusted marginal cost of existing aircraft is less than the replacement's average cost per available year. Ref. 3 extended this study to large cargo aircraft fleet. Both studies concluded that the model for decision to repair or replace an aging aircraft should be used prospectively. For example, one would estimate ahead of time when it is thought the optimum will be achieved, and have a replacement system prepared to enter service at that time.

Figure 10: C-5 Galaxy [2]

The situation today is that a large number of aging aircraft are in the fleet inventory and have to be maintained in an acceptable state of operational readiness. This situation is likely to persist for some time. Considerable advances in science and technology are needed to reduce the burden of detecting and identifying structural damage, increase the maintenance effectiveness, reduce downtime, and increase availability.

3 DAMAGE-TOLERANT AIRCRAFT STRUCTURES

Aircraft structures are built to minimize weight while increasing safety and reliability. The analysis and design of flight structures [5] takes into account static strength, buckling resistance, and fatigue life.

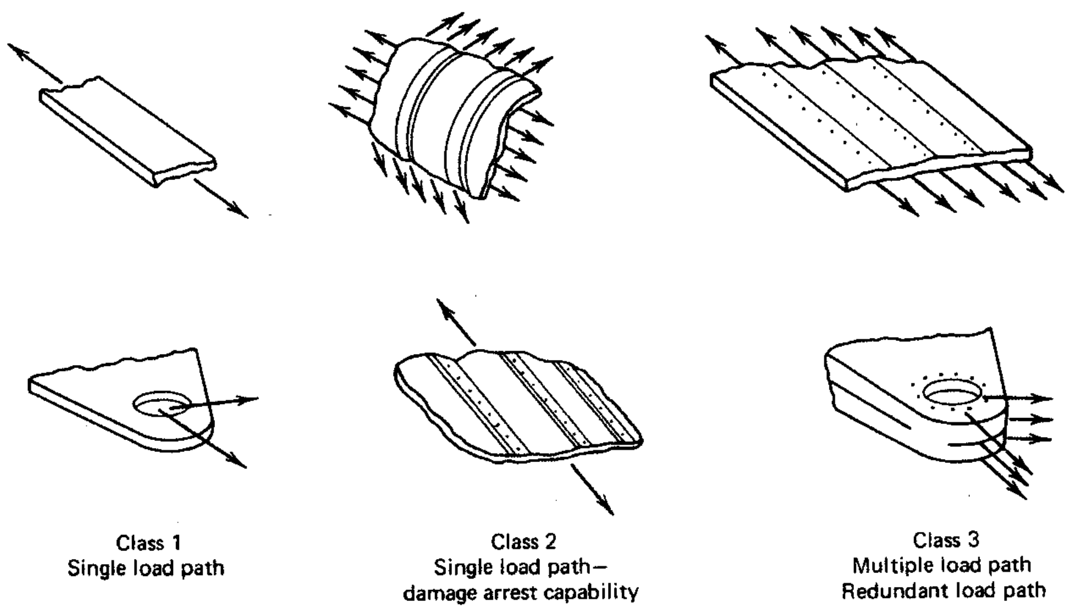

Figure 11: Structural types based on load path [6]

In order to increase the aircraft survivability in case of unexpected structural damage, flight structures have evolved from single load path to multiple load path designs and damage-arresting capabilities (Figure 11). In this way, flight structures have become damage tolerant. Current *damage tolerant* flight structures are designed to minimize the loss of aircraft due to the propagation of undetected flaws, cracks, and other damage. Damage-tolerant structures have two important qualities:

(a) controlled safe flaw growth, or *safe life with cracks*

(b) positive damage containment, i.e., safe remaining (residual) strength

A basic assumption in damage tolerant flight structures is that *flaws exist even in new structures* and that they may go undetected. Hence, any member in the structure must have a *safe life* even when cracks are present. In addition, flight critical components must be *fail-safe*.

4 FULL-SCALE FATIGUE TESTS

The safe operational life of an aircraft is determined through on full scale fatigue testing of complete test articles under simulated fatigue loading. Such full-scale fatigue testing have undeniable benefits. They discover fatigue critical elements and design deficiencies; determine time intervals to detectable cracking, collect data on crack propagation, and determine *remaining safe life with cracks* as well as the residual strength. These tests establish the proper *inspection intervals* and help in developing/testing appropriate repair methods. Full-scale fatigue testing should continue long term and stay sufficiently ahead of the fleet to allow adequate lead-time for redesign and installation of whatever modifications are required to prevent catastrophic fleet failures. However, full-scale fatigue testing are extremely expensive. Much of the aging aircraft fleet has exceeded the design fatigue life, and hence are no longer covered by the full-scale fatigue testing done several decades ago. In order to extend their service life, additional fatigue tests are being conducted.

Figure 12: Full-scale fatigue test of CF-18 aircraft [6]

5 NONDESTRUCTIVE INSPECTION AND NONDESTRUCTIVE EVALUATION

In-service inspection procedures such as nondestructive inspection (NDI) and nondestructive evaluation (NDE) play a major role in the determination of safe operational life of fail-safe structures. NDI/NDE inspections are the sole data source for structural state diagnosis and remaining life prognosis. Inspection intervals are established assuming a "detectable" crack size, a_{det}; the value of a_{det} depends on the available NDI/NDE procedure and equipment. Cracks larger than a_{det} are presumed to be discovered and repaired. The

inspection intervals are determined in such a way that an undetected flaw will not grow to critical size before the next inspection. The use of NDI/NDE techniques and the establishment of appropriate inspection intervals have progressed considerably in recent years in order to ensure the safe operation of our current aircraft fleet. Recent developments include automated scanning systems and pattern recognition methods that relieve the operator of the attention-consuming tedious decision-making in routine situations and allow the human attention to be concentrated on truly difficult cases. Nevertheless, the current practice of scheduled NDI/NDE inspections leaves much to be desired. Some large aircraft can have as many as 22,000 critical fastener holes in the lower wing alone [7]. Complete inspection of such a large number of sites is not only tedious and time consuming, but also subject to error born of the boredom of inspecting 20,000 holes with no serious problems, only to miss one hole with a serious crack (sometimes called the “rogue” crack). In addition, many inspections that require extensive disassembly for access may result in flaw nucleation induced by the disassembly/reassembly process (*inspection-induced damage*). As our aircraft fleet ages, the crack population increases, and the NDI/NDE costs greatly proliferate.

5.1 Perceived SHM contributions to structural diagnosis and prognosis

Structural health monitoring (SHM) could have a major contribution to the structural diagnosis and prognosis. Although NDE methods and practices have advanced remarkably in recent years, some of their inherent limitations still persist. NDI/NDE inspection sensitivity and reliability are driven by some very practical issues when dealing with actual airframes. Field inspection conditions may be quite different when compared to laboratory test standards.

Perhaps the major limitation of current NDI/NDE practices is the fact that NDI/NDE, as we know it, cannot provide a continuous assessment of the structural state [8]. This limitation is rooted in the way NDI/NDE inspections are performed: the aircraft has to be taken off line, stripped down to a certain extent, and scanned with NDI/NDE transducers. This process is time-consuming and expensive. This situation could be significantly improved through the implementation of a SHM system. Having the SHM transducers permanently attached to the structure (even inside closed compartments), would allow for structural interrogation (scanning) to be performed on demand, as often as needed. In addition, a consistent historical record can be accumulated since these on-demand interrogations are done always with the same transducers which are placed in exactly the same locations and interrogated in the same way.

SHM could provide an advanced utilization of the existing sensing technologies to add progressive state change information to a system reasoning process from which we can infer component capability and predict its future safe-use capacity. Through monitoring the state of structural health, we can achieve a historical database and acquire change information to assist in the system reasoning process. Advanced signal processing methods can be used to detect characteristic changes in the material state and make that state-change information available to the prognosis reasoning system. The concept of change detection can be used to

characterize the material state by identifying critical features that show changes with respect to a reference state that is stored in the information database and updated periodically. When this is performed in coordination with existing NDI/NDE practices, the structural health monitoring information performed in between current inspection intervals will provide supplementary data that would have a densifying effect on the historical information database.

Another advantage of implementing SHM systems is related to the nonlinear aspects of structural crack propagation. Most of the current life prognosis techniques are based on linear assumptions rooted in laboratory tests performed under well defined conditions. However, actual operational conditions are far from ideal, and incorporate a number of unknown factors such as **constraint effects, load spectrum variation**, and **overloads.** These effects are in the realm of nonlinear fracture mechanics and make the prediction very difficult. However, the dense data that can be collected by an SHM system could be used as feedback information.

6 CURRENT SHM/NDE FUNDAMENTAL RESEARCH PROGRAMS FUNDED BY AFOSR

The Air Force Office of Scientific Research is currently funding several fundamental research programs, as follows:

Fundamental Studies in Embedded Ultrasonic NDE is a research project aimed at studying the Lamb wave interaction between piezoelectric wafer active sensors (PWAS) and the host structure. The project is conducted at the University of South Carolina. The project PI was Prof. Victor Giurgiutiu, prior to his taking up position to AFOSR. Current PI is Prof. Y. J. Chao. The project pursues **analytical modeling, numerical simulation, and experimental validation**. Several significant results have been obtained:

(a) Selective tuning of Lamb wave modes with in-situ PWAS transducers [9]
(b) In-situ imaging of crack growth with PWAS phased arrays using our embedded ultrasonics structural radar (EUSR) concept [10] [11]
(c) Monitoring of in-situ durability and survivability of PWAS transducers installed on coupon specimens representative of structural parts [12]

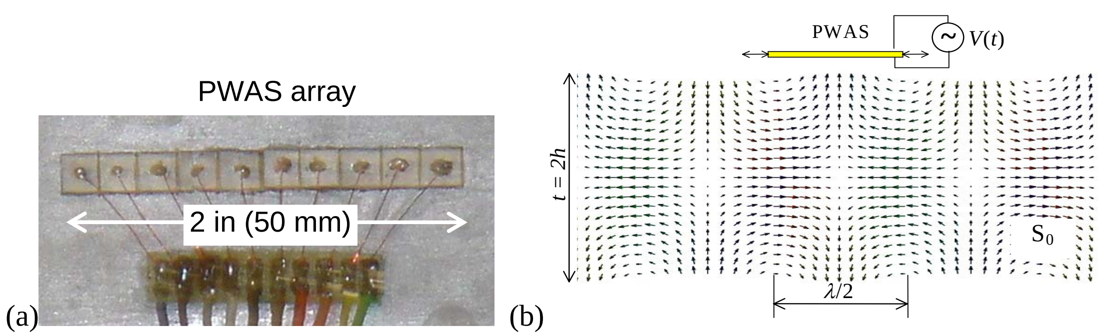

Figure 13 (a) PWAS array on an aircraft panel; (b) typical structure of S_0 Lamb waves in interaction with PWAS

Closed form solutions were developed to predict how the Lamb waves are excited by a surface mounted PWAS transducer [9]. These solutions have been developed using space-domain Fourier transform of the Lamb-waves differential equations and of the shear excitation given by the PWAS transducer. These closed form solutions were thoroughly verified by experiments

Directional Guided Waves for Large Area Structural Health Monitoring is a research project aimed at developing a novel power-efficient and long-range active SHM system utilizing guided waves generated and detected with specially tailored anisotropic microfiber piezocomposite transducers. The project is conducted at the University of Michigan by Prof. Carlos Cesnik. Recent results include a comprehensive modeling of the interaction between anisotropic piezoelectric transducers of different shapes and the support structure, which can be of either metallic or composite construction [13][14].

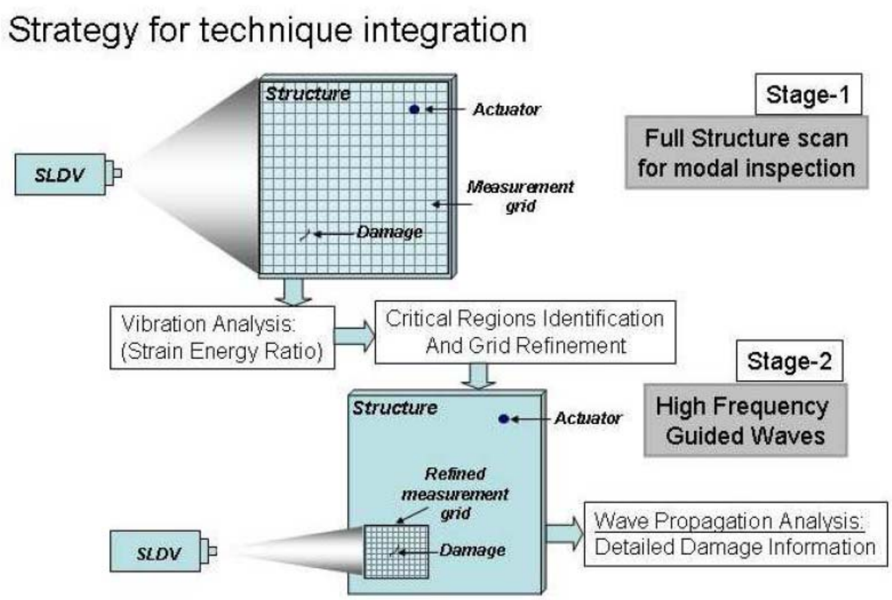

Figure 14 Integration of modal inspection and wave propagation analysis for improved damage detection [15]

Rapid and Robust Dynamics-Based Nondestructive Method to Monitor Structural Health is a project aimed at developing improved damage index algorithms for cracks, disbond, delamination, and corrosion damage in aerospace structures using both vibration response and wave propagation techniques in conjunction with a scanning laser Doppler velocimeter. The project also aims at developing software for the automation of the SHM process and integration into a turnkey product. The project is conducted by Mr. Vinod Sharma

of Millennium Dynamics Corp. Inc., in collaboration with Prof. Massimo Ruzzene and Prof. Sathya Hanagud of Georgia Institute of Technology [15].

In-Situ Adhesive Bond Assessment for Aerospace Structures is a project aimed at developing a guided-wave in-situ approach to the detection, localization, and assessment of damage in adhesively bonded structural joints. The project considers, but is not limited to, lap-shear and tear-strap-to-skin adhesive joints, composite-to-metal joints, etc. The focus of the project is on developing a guided-wave ultrasonics architecture that can be implemented in-situ with permanently attached wafer sensors. The project is conducted at the University of California San Diego by Prof. Michael Todd and Prof. Francesco Lanza di Scalea.

Probability-Based Integration of Structural Health Monitoring into the Aging Aircraft Sustainment Program is a project aimed at developing a probabilistic framework to fuse the two processes that are at the SHM foundation, (a) damage diagnosis, and (b) remaining life prognosis. Both processes entail much uncertainty in the sensor data, structural modeling, and material and geometric properties. While a continual flow of information about damage existence and propagation is being extracted from the raw sensor data, the probabilistic framework would allow an SHM system to progressively improve its accuracy, and progressively narrow the spread of the predicted material states and remaining useful life leading to ever more accurate prognosis with confidence. First, the project will develop a probabilistic framework and demonstrate by simulation the benefits such a framework can impart on the SHM process. Second, the project will demonstrate the application of the probabilistic framework to a specific SHM system, focusing on the use of Bayesian updating to improve the probability of detection (POD) models and the prognosis accuracy. The project is conducted in collaboration by Prof. Raphael Haftka at the University of Florida and Prof. F. G. Yuan at North Carolina State University. Recent results include the use of test data to update failure stress [16]; extrapolation of reliability estimates from observed levels to unobserved level [17], and probabilistic design optimization [18]

Nonparametric System Identification Based on Slow-Flow Dynamics with Application to Damage Identification and Uncertainty Quantification is a project aimed at developing an effective, straightforward, non-parametric method for characterizing *strongly nonlinear, complex, multi-component systems* using the slow-flow dynamics. The ultimate scope of the project is to develop such a method for nonlinear systems that will be as utilitarian as the experimental modal analysis is for linear systems. The project will utilize the method of complexification and averaging (CxA) that was previously developed to extract the slow flows (periodic solutions) of strongly nonlinear systems. Initial laboratory experiments have yielded a relationship between the slow flows and the intrinsic mode functions (IMF) that arise from empirical mode decomposition (EMD), which is at the root of the Hilbert-Huang Transform (HHT). The project will attempt to use this relationship to understand the physical

basis for the HHT and to facilitate a new, nonparametric identification method for strongly nonlinear, nonstationary systems. Using the HHT and wavelet transform mathematical tools, the project will attempt to identify key transitions in the behavior of strongly nonlinear systems. Between these transitions, the project will develop low order dynamic models that adequately replicate the system behavior for system design and control. If the observed transitions represent various stages of damage, then the method will yield a novel procedure for health monitoring. The project is conducted at the University of Illinois at Urbana-Champaign by Prof. Lawrence Bergman, Prof. Michael McFarland, and Prof. A. Vakakis.

Quantifying Structural Variability for Improved Health Monitoring is a project aimed at incorporating the effects of variability observed during empirical testing into the physics-based modeling and classification during the structural health monitoring system development process. The project will demonstrate the benefits of including variability into structural health monitoring system design. Improved accuracy and increases robustness with regard to the range of conditions over which the classification can be reliably performed is expected. The project is conducted by Mr. Mark Derriso at the Air Force Research Laboratory, Air Vehicles Directorate in collaboration with Dr. Jeffrey R. Calcaterra from the Materials and Manufacturing Directorate and Dr. Steven Olson from University of Dayton Research Institute.

Computational and Experimental Methods in Nondestructive Evaluation for Damage State Characterization is a project aimed at improving the characterization of small damage (cracks, corrosion) with eddy current and ultrasonic methods in complex structures by applying computational methods that simulate the nondestructive evaluation (NDE) process. Such simulation studies can be used to gain a fundamental understanding of the difficulties involved in the NDE damage characterization problem, which has to differentiate and size small material discontinuities in complex structures in the presence of coherent noise. This fundamental understanding and the associated modeling capabilities will open the path towards better data analysis and damage classification methods that explore multi-dimensional signal processing and model-based classifiers via inverse methods. The project is conducted at the Air Force Research Laboratory NDE Branch by Dr. Kumar Jatta in collaboration with Mr. Jeremy Knopp and Dr. Eric Lindgren, from the same branch, and Dr. John Aldrin from Computational Tools, Inc. [19][20][21].

Life Prediction and Durability of High Temperature Materials is a project aimed at developing physically based analytical and numerical models for predicting the life of advanced high-temperature aerospace materials under realistic service conditions. The ultimate goal of the project is to enable the rational design, tailoring, and sustainment of new revolutionary materials such as to maximize their durability, reliability, and life-cycle affordability and to shorten the material-development-to-component time line in a sustainable

way. A probabilistic model based on small crack growth was shown to successfully predict the lower life limiting behavior of certain titanium alloys. This model accounted for the variability in small crack growth behavior and crack initiation size. A detailed microstructure base 3-D characterization and modeling was initiated to understand the uncertainty in local stress and deformation around the initiation sites. High-magnification full-field deformation-tracking experiments were conducted to determine the effect of orientation on the stress-strain behavior of material grains. The project is aiming at extending and quantifying the reduced-uncertainty worst-case analysis, emphasizing mechanistic and time-dependent contributions to uncertainties. The effect of notches and residual stresses will be investigated. Three dimensional microstructure based analysis will be conducted to determine the variability in stress around the crack initiation sites. These models will be integrated in the analysis of damage-induced signature of a cracked turbo-engine integrated bladed rotor [22][23][24][25][26].

A Multidisciplinary Approach to Health Monitoring and Materials Damage Diagnosis is a multidisciplinary university research initiative (MURI) program, which started in mid-2006. The program comprises the collaboration between four major universities: Arizona State University, Johns Hopkins University, University of Southern California, and Virginia Polytechnic Institute and State University. The team leader is Professor Aditi Chattopadhyay from Arizona State University. Preliminary results include the time-frequency classification of structural damage [27] and modeling of structural nonlinearities using reduced order models [28].

7 NEEDS AND RESEARCH DIRECTIONS IN STRUCTURAL DAMAGE ASSESSMENT

The science of structural health monitoring and structural damage assessment is still in its infancy. Though remarkable progress has been achieved in some proof-of-concept demonstration, the overall scope and breadth of the subject is still generally unexplored. The science and engineering community is gradually starting to realize the wide implication of deceptively simple question: could a structure tell us the state of its health, just like the human body "hurts" when it is injured or tired? How can we negotiate the graceful progression of a flight structure from "prime time" into the middle age and gradually into well-earned retirement? The science and engineering community has recently created a dedicated publication (*Structural Health Monitoring – An International Journal*, Sage Pub., UK), and several other established publications have refocused to include structural health monitoring into their central vision. A number of international conferences have proliferated on the subject, as for example the *International Workshop on Structural Health Monitoring* which is held every other year at Stanford University, California, USA, and the *European Workshop on Structural Health Monitoring* which is held in alternate years in various locations in Europe. Many of the well established long-running conferences in NDI, NDE, materials, etc.

have recently added sections on structural health monitoring. Recently, an informal discussion group, *Structural Health Monitoring -- Aerospace Industry Steering Committee (SHM-AISC)* has been set up with participation from industry, government agencies, and academia with a common interest in this emerging field [29].

There are several research directions of high interest to the SHM community. SHM-AISC is generally interested in permanently-attached "sensor-actuator networks that could automatically assess the integrity of aircraft structures in order to reduce maintenance costs and downtime by ending manual inspections" [29]. To achieve this goal, considerable research, implementation, validation and certification work needs to be performed. The subject is clearly multidisciplinary, spanning from the analysis and design of flight structures to sensors and actuators electronics and data processing. The implementation path will travel from fundamental basic research, through applied research, to wide-spread industrial dissemination. It is difficult to predict all the research topics that will be likely to be encountered along this path. The author of the present article would like to articulate two such topics with immediate relation to the structural mechanics area, as shown next.

7.1 Uncertainties-based structural analysis:

The science of flight structures analysis needs to achieve the capability to predict the distribution of flaws and service-induced damage at fleet level and on each individual aircraft. The *issues* at hand are that there is considerable variability in several areas:

- material processing and component fabrication
- maintenance actions
- changing mission profiles

The *science enablers* that must be developed would include:

- Quantifiers and descriptors for actual variability in each of the above listed areas
- Uncertainty-based analysis at structural multi-levels
- Sensing materials and embedded systems to track mission effects on the structure and elaborate statistical mission profiles in real time

7.2 On-demand structural health bulletins -- structural diagnosis and prognosis:

There is a clear need for the following capabilities:

- On-board health monitoring systems which could be viewed as "embedded NDE"
- Data interpretation of the measured results that would give the commander a state-awareness risk-based approach to mission planning and aircraft maintenance

The *science enablers* that must be developed would include:

- Multi-field models and predictors of the sensor-structure hybrid behavior

- Structural analysis which can predict the sensors response as damage progresses throughout the structure
- Risk-based structural analysis using state-awareness descriptors and risk-tolerance levels
- Data mining methods for structural damage detection, life prediction, structural/system prognosis

The above two topics are not exhaustive. Other topics would most like emerge as the science and engineering of structural health monitoring matures. Important to realize is that the field is still mostly unexplored, and that sustained research and development work is required to bring it to maturity and fruition.

8 CONCLUSIONS

This paper has presented the perspective of the Structural Mechanics program of the Air Force Office of Scientific Research on the damage assessment of structures. It was found that damage assessment of structures plays a very important role in assuring the safety and operational readiness of Air Force fleet. The current fleet has many aging aircraft, which poses a considerable challenge for the operators and maintainers. The nondestructive evaluation technology is rather mature and able to detect damage with considerable reliability during the periodic maintenance inspections. The emerging structural health monitoring methodology has great potential, because it will use on-board damage detection sensors and systems, will be able to offer on-demand structural health bulletins. Considerable fundamental and applied research is still needed to enable the development, implementation, and dissemination of structural health monitoring technology.

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